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Synthesis and Characterization of Organic Conducting Polymers for Advanced Materials

DR. K. S. LAMANI
Associate professor, Department of chemistry, C.S. Bembalagi, S.M.R.Palaredha science and G.L.Rathi commerce college Ramdurg

Abstract- Polymeric materials have become integral to the development of modern technology. They are lightweight, mechanically robust, highly tunable, and find widespread application in electronic, energy, sensing and biological systems. Among functional polymeric materials, organic conducting polymers are significant as they offer the unique combination of mechanical attributes typical of commodity polymers and the electrical and optical properties known to be present in inorganic conductors. These conjugated polymer systems possess highly extended delocalized electron networks which transport electric charge. Charge transport and tunable electronic properties lead to conductive polymers such as polyaniline (PANI), polypyrrole (PPy), polythiophene (PT), poly(3,4-ethylenedioxythiophene) (PEDOT), of tremendous importance in modern and next-generation advanced materials (Heeger, 2001). However, current conductive materials possess inherent limitations in their mechanical flexibility, processing requirements, electrical conductivity, stability under environmental stresses, etc, therefore light-weight flexible robust organic conductive polymers are extremely beneficial for many applications that go beyond conventional solid-state devices and for next generation systems. This conceptual research work puts forth a research strategy on synthesis and characterization of organic conductive polymers utilizing the approaches, like chemical and electrochemical polymerization, modulation of polymer backbones via modification strategies, and regulated doping approach so that conductivity and other properties of the materials will be improved. The conceptual scheme also includes the detailed structure studies of the prepared polymers by using different analytical techniques including FTIR, NMR, UV-Vis, XRD, scanning and transmission electron microscopic images and thermal analysis methods for their molecular structural, morphological, crystalline and stable behavior and to analyze their electrical conductive properties. Mechanical property studies, electron transport mechanism analysis and stability against environment are proposed for different conducting polymer materials. The contribution of this conceptual investigation would be the development of novel advanced conductive polymers with better structural and property correlation, and applicability on organic devices, electronic sensing, energy storing device, bio-medical uses, chemical and biological sensor and flexibility electronics etc. Thus, the study of organic conductive polymers synthesis, analysis, application is a successful method toward innovative and useful materials in modern days.

Keywords: Conducting polymers, Organic electronics, Polymer synthesis, Polyaniline, Polypyrrole, Characterization

I. INTRODUCTION AND BACKGROUND RELATED TO THE STUDY

Organic conducting polymers represent an exciting area of advanced functional materials that effectively blend the attributes of traditional polymer systems such as flexibility, low density, chemical versatility, and processability with those typically seen with metallic materials and inorganic semiconductors – electrical conductivity and electro-optic activity. Basically, they are defined as a polymer molecule which possesses a delocalized pi-electron system on its chain that is responsible for transport of an electrical charge. A chain made of alternating single and double bonds makes it possible for electrons to travel freely throughout the molecule with doping or some appropriate method. Conceptually, a conducting polymer can be pictured with a polymer backbone with electrically conductive pi-electron path in the molecule making this material very valuable in devices in electronics, storage of energy, as sensing and in medical purposes (Heeger, 2001). Through discovery and use of conductive polymers we have gained more insight into polymer and its properties, as polymers used to be known as excellent insulators. But research on polyacetylene(–CH=CH)n) shows that it possible to achieve much higher conductivity just through doping with an electron acceptor or donor, which results in semiconducting and metallic-like electronic behavior with control of amount of doping dopant (Shirakawa et al., 1977). Research such as this one have put the foundation under the development of modern polymer conductors, it gives an inspiration to study conductive organic structures, such as polypyrrole, polyacetylene, polythiophene, polyaniline, and PEDOT etc. With its better stability and performance under ambient conditions and different devices (MacDiarmid, 2001); Moreover, electrical conductivity was an especially striking observation and development in conductivity, its importance in the field has been honored with Nobel Prize in chemistry award given in 2000; The organic conducting polymers have numerous potential advantages such as light weight, mechanical flexibility, tunable conductivity etc and make their application in flexible electronics, organic light emitting diodes, solar cells, chemical sensors and in electric charge storages feasible etc. But it has other problems such as stability, environmental stability, conductivity controlling and long-term durability that make conductive polymer research a subject of constant improvement on synthetic, electronic, and materials aspect of conducting polymers. Understanding its chemistry, electrical property and historic background is therefore crucial on our path to design better future materials.

Importance of Conducting Polymers in Advanced Materials

Due to their interesting combination of electrical conductivity, mechanical flexibility, light weight and chemical tunability, organic conducting polymers have become key advanced materials applicable in fields such as electronics, energy, sensing, and medicine; in electronic fields, conductive polymers can offer a practical alternative to conventional inorganic semiconductors by the virtue of their solution processability, optical activity and ability to be applied to flexible substrates in organic light-emitting diodes (OLEDs), flexible displays and organic field effect transistors as their semiconducting characters contribute to the charge transport, photo-emission, and miniature design of electronic devices (Facchetti, 2011); conducting polymers have occupied an important position in the exploration of sophisticated energy storage and conversion systems attributed to their reversible electrochemical response, high surface area and high electrical conductivity making them useful electrode materials for supercapacitors, secondary batteries and photovoltaic devices the properties result in advanced charge storage capacities, efficiencies for the conversion of energies and increased flexible capability of the devices(Snook et al., 2011); as another major research and application area for conductive polymers, their changes in electrical properties can be triggered upon the chemical, biological and environmental stimuli which permits the construction of reliable sensors with high detection sensitivity, selectivity, and reliability such as chemical sensors, gas sensors and biosensors (Gerard et al., 2002); additionally, the combination of conductivity and bio-compatibility permits the wider use of conductive polymers in the fields concerning biological and medical issues as an interesting alternative materials, like in the systems for tissue engineering and drug delivery where the conductive polymer scaffolds can provide stimulation to cells and control release of drugs. Materials like polyaniline, polypyrrole, polythiophene, and PEDOT have been investigated due to their tunable electrical characteristics, changeable mechanical properties and possibility to obtain tailored functionalities of them; hence the development of conductive polymers using novel synthesis, characterization and processing methods is promising for the discovery of novel advanced materials for future generation electronic devices, green energy technologies, intelligent sensors, and medical fields.

II. CHEMISTRY OF CONDUCTING POLYMERS

Conducting polymers are considered a significant class of materials and have gained considerable interest and application owing to the existence of an extensive delocalized π electron system along the polymer backbone which arises due to alternate single- and double- bond formation. The delocalized π systems present in conductive polymer systems provide continuous paths through which charges can be transported and as such render the conductive organic materials semiconducting or conductive upon chemical or electro- doping process; unlike non-conducting polymer structures that present isolated systems, the conductive polymer backbone extends such that the charge can be transferred by the movement of the π electrons through the structure yielding optoelectronic, conductive and versatile electronic property to organic materials (Skotheim & Reynolds, 2007). Prominent among these materials includes the research of polyaniline (PANI) which is highly valued and has undergone significant scientific and technological developments owing to its stable nature under different environmental conditions, convenient synthesis routes, tunable redox activities, reversibility, and conductivity modulation which arises through protonic acid doping of the repeating aniline unit [-CH-NH-CH-NH-]; on its turn, polypyrrole (PPy) known as a stable and readily available conductive polymer with good electrically conductive properties, also shows superior stability and great biocompability which allows it to find widespread use in different sensors, energy storing devices, and in different biological applications (Guimard et al., 2007); likewise, polythiophene (PT) and its derivatives are highly attractive owing to its fine optically and electronically active property, changeable bandgap to a certain level as well as charges and ability to travel along their backbone for possible application in organic transistors and optoelectronic device such as transistors and photovoltaics; hence, to exploit conductivity polymers, their relation to structure and delocalization will enable charge transport.

III. RESEARCH PROBLEM

While considerable progress has been made in developing conducting organic polymers for advanced materials, their use in next-generation applications is hindered by intrinsic drawbacks (such as mechanical durability and chemical stability) linked together through processing behaviors and conductivity-flexibility tradeoffs, because many intrinsically conducting polymers have rigid conjugated backbones contributing efficient charge transport, but diminishing flexibility/mechanical strength/ elasticity and resistance towards repeated deformation (e.g., in terms of wear-resistance) needed for the applications such as wearable devices and micro electronics (Heeger, 2001); Furthermore, ambient exposure to such detrimental factors as O2, moisture, high temperatures, etc., would directly lead to inevitable changes in oxidation states, doping levels or morphologies of the conductors which result in instability in their electrical performance and overall long-term durability (McQuade et al., 2000); The processing of organic conducting polymers to film, fibers, coatings and some sort of defined architectures is also of great interest as some conductive polymers are neither soluble in conventional solvents nor have melts suitable for further processing due to the tightly packed backbone which promotes pi-stacking structure among macromolecules, suggesting the importance of exploring novel chemical modification approaches on conducting polymers enabling them as solution processable (e.g., with functionalized side chain or forming soluble or melt processable polymers). Moreover, the more conjugation or increased doping leads to higher electrical conductivity as well as decreased flexibility of material structures and that presents an important conductivity-flexibility trade-off, which could not be ignored in the field of developing flexible conducting polymeric materials (Kwon et al., 1997); So continued efforts are to develop new architectures with designed molecular ordered structures, improved intermolecular chain interactions, optimized conjugated backbone with balanced mechanical properties, conductivity and processed behaviors through systematic integration with control in polymerization conditions. In addition, advanced polymerizations methods should allow precise control over molecular weight, Morphology, doping levels and process abilities. More importantly, improved synthetic strategies to provide both enhanced electron conductivity, electron-hole transporting ability and also mechanical integrity, environmental stability and process compatibility will be paramount for real application toward electronic and energetic technologies and sensing and biomedical areas.

IV. AIM OF THE STUDY

This conceptual study focuses on designing a cohesive conceptual framework through which to design, synthesize, characterization and utilization of organic conducting polymers having superior electrical, mechanical, thermal and functional properties through establishing structure-properties correlations between molecular architecture, Conjugated backbone Structure, eletcroin delocalization degree, Oxidation State, doping behavior, morphology and Charge Transport Behavior using traditional conducting polymer system namely Polyaniline, Polypyrrole, Polythiophene and PEDOT as archetypal conducting polymer material systems toward development of new and sophisticated materials (Heeger, 2001); the study would further endeavor to propose innovative concepts for chemical and electrochemical polymerization that would allow further control over structural features of polymers, their molecular ordering, film formation, functionality etc coupled with the effective chemical and electrochemical doping and structure modification routes for enhanced conductivity at compatible levels which does not trade off with their mechanical elasticity and ENVIRONMENTAL stability; in addition, a rigorous characterization model encompassing techniques from spectroscopy, microscopy, structural studies, thermal, Electrical as well as mechanical characterization is needed in the framework to establish a clear understanding regarding how molecule structure & morphology affect performance, Skotheim & Reynolds, 2007); it requires the framework to highlight possibilities for better processability, endurance, charge transport and integration with substrate materials relevant to tech applications; to enable creation of light weight and stretchable functional materials; to conceptually establish links among structure property of polymers and applications related to flexible electronics, electronic devices (organic electronics),Energy storage system, Chemical & biological sensors, and Biomedical Technology; and ultimately the conceptual framework to identify various crucial gaps & opportunities toward desired polymer constitution of superior conductivity, Stability, processing and Mechanical properties.

V. CONCEPTUAL RESEARCH METHODOLOGY

Rational polymer design is proposed as the starting point; candidates for conducting polymer applications will be chosen based on desired conductivities, chemical/environmental stability, mechanical flexibility, processability, and appropriate application suitability and then conjugated monomers will be designed in a way to support suitable delocalization, allowing electrical charge transport (Heeger, 2001); the application of monomer selection will lead to polymer formation through chemical or electrochemical polymerization, after which doping modification, purification, analysis (spectroscopic, structural, etc) and final performance testing will be conducted (Figure 1) showing a correlation between the chemical composition of material and its resulting properties; chemical oxidative polymerization will be employed as the primary methods of synthesis, as it provides a way to synthesize polymers from monomer using an oxidant (Skotheim & Reynolds, 2007) the key synthesis variables to explore would be concentration of monomer, oxidant: monomer ratio, reaction temperature, suitable solvent and reaction time; electrochemical polymerization could also be used as, polymers can directly be deposited onto an electrode where the polymerisation would be conducted under an applied current or potential, with variables including electrode shape, monomer concentration, solvent/supporting electrolyte and applied time being critical for obtaining films of the required shape and quality, following formation of any polymer products purification is necessary and material properties will be assessed using a range of analysis techniques, culminating in comparison of materials based on the optimized balance required for each specific application.

VI. CHARACTERIZATION METHODS

Accurate characterization of synthesized organic conducting polymers to obtain their chemical structure, arrangement and organization of molecules, morphology, electronic properties and thermal stability, is necessary. The characterization of monomers, polymers as well as treated samples can begin with the use of Fourier Transform InfraRed spectroscopy to reveal characteristic functional groups, polymer- backbone vibrations to indicate successful monomer conversion, conjugated- bond formation, and possible chemical modification. A nuclear magnetic resonance (NMR) spectroscopy reveals detailed molecular level structural information with the 1H NMR technique providing details of proton environment and 13C NMR the chemical environment and connections of carbon species in the polymer framework although higher-resolution solution NMR may have its limitation when analyzing poorly soluble or aggregation of conductor polymers (Skotheim & Reynolds, 2007). Investigating electronic transitions associated with conjugated Pi systems through UV-visible spectroscopy allows estimation of characteristic optical band- gap information, helpful in correlating molecular

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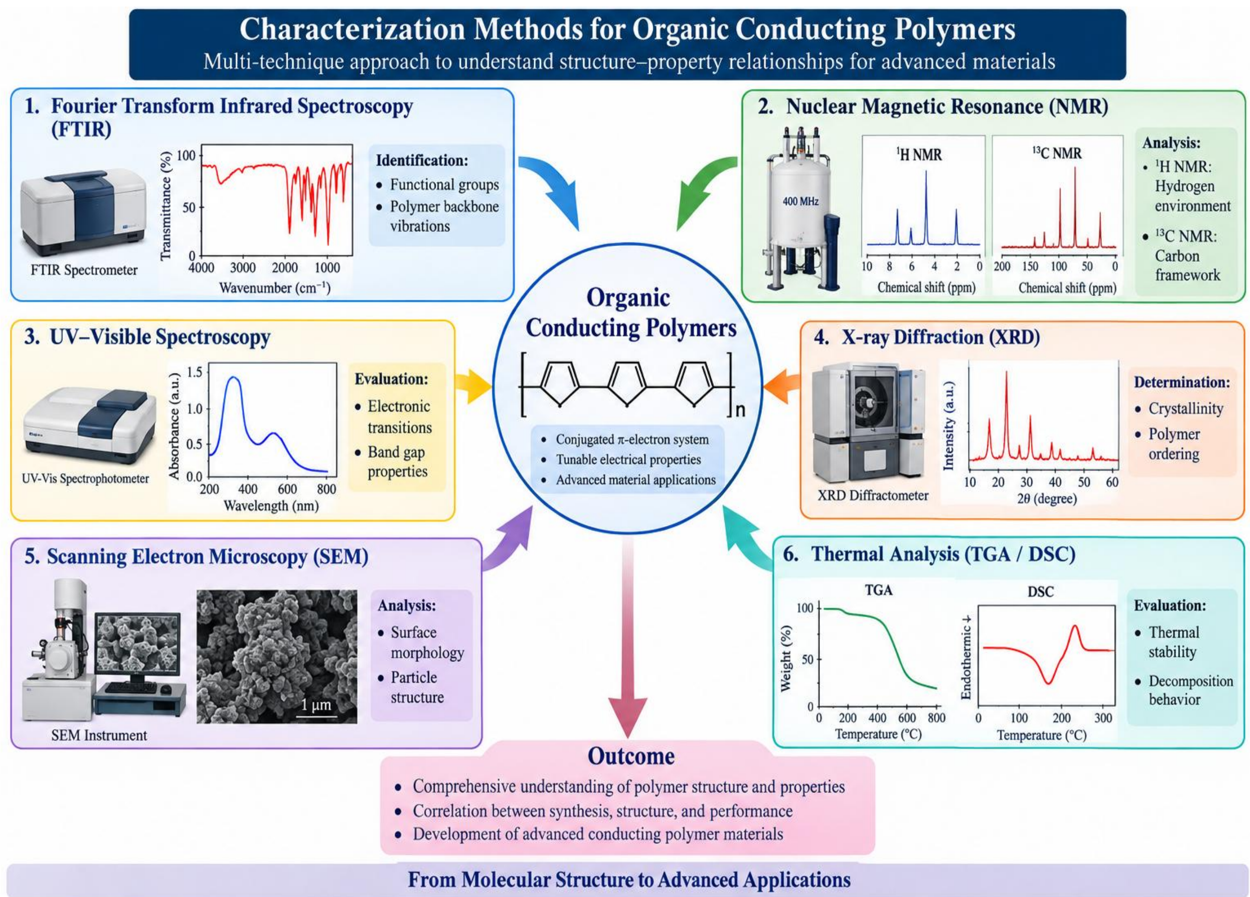
conjugation and doping state to their electronic behavior (Heeger, 2001). A measurement of crystallinity, intermolecular organization and structural arrangement which directly affects charge transport as well as physical properties can be made by X- ray diffraction (XRD) while the morphological behavior of particles dimensions, surface morphology and macroscopic aspect developed during polymer synthesis and treatment could be evaluated by scanning electron microscopy (SEM). Moreover, thermal analysis techniques such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) determine their mass loss upon heating, the temperatures of decomposition and transitions of materials, and operational stability; therefore, to verify if prepared samples can withstand higher temperature. Combining FTIR, NMR, UV-visible spectroscopy, X-Ray diffraction, SEM, TGA and DSC creates a multidimensional approach towards obtaining meaningful data for both structural information and the relevant properties of the materials



Above diagram showing Synthesis and Characterization of Organic Conducting Polymers

VII. DISCUSSION

A further improvement in the physical properties of conductive polymers is anticipated to be obtained through controlling molecular architecture-electron mobility, electrical conductivity, etc. As stated previously, high conductivity is achievable by tailoring conjugated polymer backbone, enhancing delocalization of -electron and charge carrier mobility, and optimization of doping level, on the other hand enhanced chemical and thermal stability will be attained by monomer selection, suitable structure modification, careful choice of polymerization conditions and use of protecting group, which can reduce the degradation rate and the electrical conductivity stability after doping Heeger. Better processability of conductive polymers can also be realized through molecular design, such as improved solubility, film-forming property, flexibility and compatibility, thus enabling their use in advanced devices. However, controlling conductivity and chemical stability is only a part. If we want conductive polymer for different technological applications, then another key thing is its processability, like solubility, formability for films etc. These properties are primarily determined by intermolecular and intramolecular interactions in molecules and can be modified through molecular architecture approach. Relationship between structure and properties. The structural basis of a given conductive polymer defines the arrangement of molecular structures, which determines charge transport mechanism (especially electron transport in conjugated systems and through/in dopant) which then defined electrical properties (conduction ability), mechanical properties (strength, flexibility), and so on of polymeric materials, based on which these polymer can be used for many practical applications such as portable devices, energy storing elements, smart material or biomedical application. Therefore, it can be concluded that structure-property relationship plays a fundamental rule in organic conducting polymer science and technology. By controlling and designing appropriate structure can produce a conductive polymer which is good balanced in the sense of conductivity, chemical/thermal stability, processability.

VIII. SIGNIFICANCE OF THE STUDY

Research on the synthesis and characterization of organic conducting polymers is significantly interesting because these materials contribute to a major development in polymer chemistry; it offers evidence to show that organic macromolecules could be designed with programmable electrical, optical and functional performance; this would achieve through rational molecular design, control of conjugated backbones, doping etc.; scientifically, study on conducting polymers expand fundamental knowledge on the electronic structures, mechanism of charge transport, molecular interactions of polymers, and structure-property relationships of polymeric materials by better understanding on the conjugated backbones, oxidation states, crystallinity, doping interactions will allow greater depth in electronic conductivities of materials (Heeger, 2001); the study provide insight into phenomena of charge carrier generation, mobilities and pathways which are valuable to optimize the electronic performance and multifunctional property of the polymers; technologically, conducting polymers allow development of flexible and lightweight electronic components due to the excellent mechanical stability, solubility processing and tunable conductivities, this enable development for flexible displays, organic electronics devices, wearable sensors and further next-generation energy devices; and also useful components for energy storage device i.e. Batteries, supercapacitors, photovoltaic devices, due to electrochemical properties of conductor polymer as efficient charge storages (Snook et al., 2011); industrially, development of conductor polymer system will trigger innovations in materials industries and offer alternative materials that substitute the stiff inorganic polymers, and create functional polymer materials with ideal electrical, mechanical and environmentally responsive properties; continuous enhancement in synthesis methods, characterization techniques, processing methods would eventually lead to scalability and commercialization of conducting polymer devices over industries such as electronic industries, energy sectors, sensing applications and biomedical fields; thus this study contributes a significant role to develop functional polymers through linkage of chemistry on polymer structure, electronic properties, and practical application engineering.

IX. LIMITATIONS OF THE STUDY

It seems clear that while intrinsically conducting polymers possess great potential in advanced functional materials, there are various weaknesses that limit their wide technology applications such as controlling polymer structures, providing long-time stability, optimizing fabricating methods and making it economic for industrial production processes. Among them, an accurate control of polymer architecture becomes increasingly necessary because variation in molecular weight, chain alignment and length of conjugation, oxidation state, defects etc during polymerization will exert great influence on the electronic conductivity, morphology, mechanical properties, electrical conductivity and whole physical properties of polymers; which leads to significant difficult to obtain reproducible highly optimized conducting polymers (Skotheim & Reynolds, 2007); at the same time, stability in conducting polymers also pose serious problem. For many conducting polymers, conductivity and physical structure will be altered due to presence of various environmental factors including oxidation, moisture and temperature change and also dopant migration in the practical devices; thereby shortening the working life (Heeger, 2001); in addition to them, fabricating problem, such as insoluble properties, difficulties for melts fabrication and to produce uniform film and complex device, is also a limiting factor in many conjugated polymers to their broad use, necessitating further chemical modification or complex process for industrial fabrication; there will be further complicated problem in synthesis of intrinsically conducting polymers on a large scale as laboratory techniques, for example synthesis reaction conditions, purity of polymer and quality, etc, will be increasingly serious when scaling up the production rate (Dillon & Raks-Miyake, 2000); while new synthesis and fabrication process like controlled polymerization, special catalysts, composite formation, Nanocrystal preparation using microemulsion technique, and use of special process can enhance or improve some electrical and mechanical properties for a limited range but raise some issues such as increased cost of production, which further reduce its competitiveness over traditional polymer systems (Chaudhari & Patil, 2002); consequently, efforts will need to concentrate on design and realization of the structures of polymers with long stability and tunable property and to find efficient and economical way for industrial production of such conducting polymer based materials with electrical, mechanical and thermal properties optimized together for their wider applications in next generations materials.

X. CONCLUSION

Organic conducting polymers have emerged as highly important functional materials because their unique combination of electrical conductivity, mechanical flexibility, lightweight characteristics, and chemical tunability provides significant opportunities for the development of advanced technological systems beyond the limitations of conventional polymeric and inorganic materials; the ability to control electronic properties through conjugated molecular structures, oxidation states, and doping processes has established conducting polymers such as polyaniline, polypyrrole, polythiophene, and PEDOT as valuable platforms for applications in flexible electronics, energy-storage devices, sensors, and biomedical technologies (Heeger, 2001); rational synthesis strategies combined with advanced characterization methods play a critical role in improving material performance by enabling precise understanding of the relationships between polymer architecture, charge transport behaviour, morphology, thermal stability, and functional properties; techniques including spectroscopy, diffraction analysis, microscopy, and thermal evaluation provide essential information for optimizing molecular design, processing conditions, and application-specific performance (Skotheim & Reynolds, 2007); furthermore, successful advancement of conducting polymer technologies requires integration of chemistry, physics, materials science, and engineering principles to achieve controlled synthesis, efficient charge transport, mechanical durability, and scalable fabrication approaches; interdisciplinary collaboration allows the development of innovative polymer systems capable of meeting the demands of modern technologies, including flexible electronic devices, sustainable energy solutions, intelligent sensors, and biomedical materials; therefore, continued research into molecular design, characterization, and application-driven optimization will remain essential for creating next-generation organic conducting polymers with improved performance, stability, and practical technological value.

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